Data assimilation of rheology on ice shelves in Antarctica using a new finite element formulation of rifting and faulting processes.

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JPL

Ice Sheet System Model

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Outline

1. Introduction
2. Faults/Rifts modeling.
3. Ice rheology Brunt Ice Shelf.
4. Ice rheology Larsen C Ice Shelf.
5. Conclusions.

1 Introduction

- Crevasses that penetrate through thickness create rifts that influence ice flow on ice shelves in a major way.

- Rifts can close when longitudinal stresses become compressive enough -> rifts become faults where tangential friction along flanks drives ice flow.

- Rifts filled with water are inherently unstable (when non-linear creep flow law is considered) -> wiggling between rift and fault state. Melange stabilizes this process.

- We present new finite element model, embedded into ISSM (Ice Sheet System Model), to model contact mechanics of faults, and ice flow around rifts filled with melange.

- We apply this new model to invert for ice rheology on Brunt Ice Shelf and Larsen C Ice Shelf.

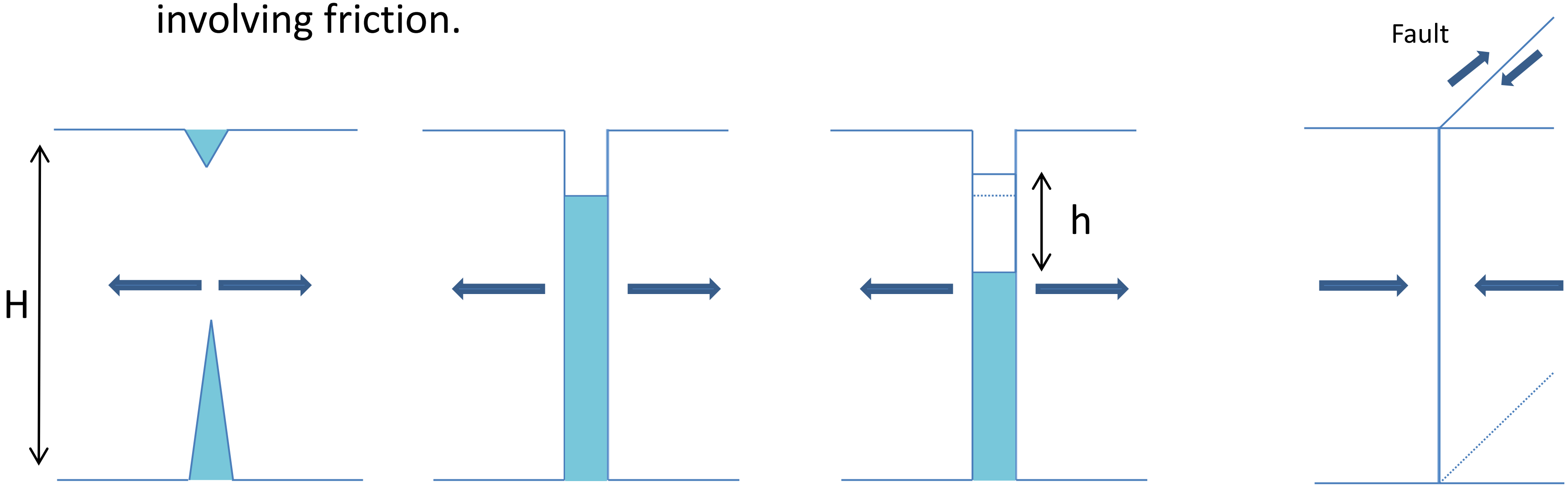
2 Rift/Fault modeling.

Several types of rifts/faults can be observed in ice shelves:

- surface and bottom crevasses in the process of creating rifts.

- rifts filled with water or melange: opening flanks on both sides of the rift.

- fault: rift that stopped opening and is closing, with contact between both flanks, involving friction.



Surface and bottom crevasse   Rift filled with water   Rift filled with melange

Boundary conditions for opening rift:

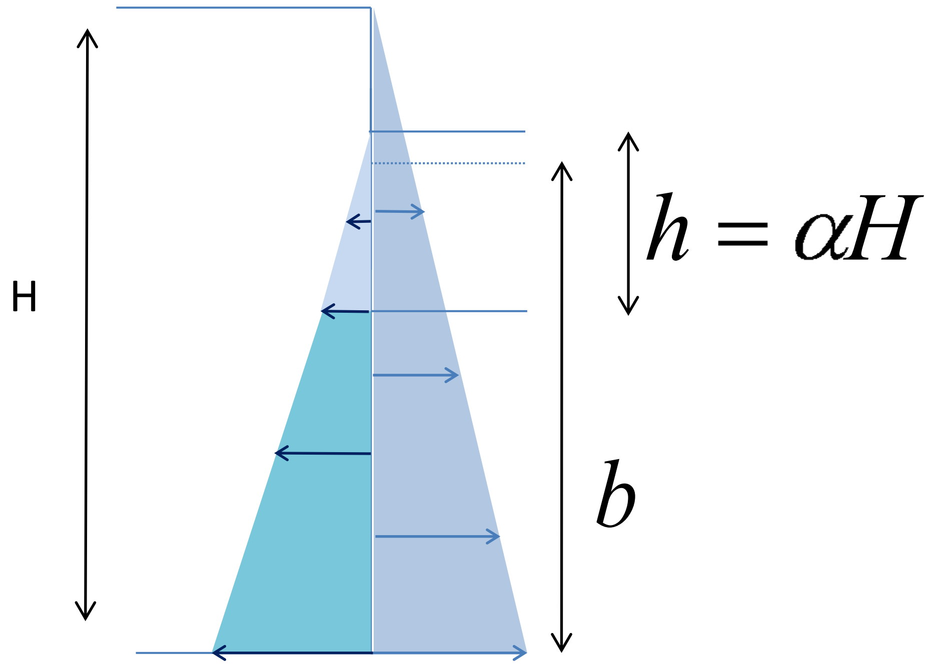
$$P = P_{litho} - P_{air} - P_{melange} - P_{water}$$

$$P_{litho} = \frac{\rho_{ice} g H^2}{2}$$

$$P_{water} = \frac{\rho_{water} g \left[b^2 - \left(\frac{\rho_{ice}}{\rho_{water}} \alpha H \right)^2 \right]}{2}$$

$$P_{melange} = \frac{\rho_{ice} g (\alpha H)^2}{2}$$

$$P_{air} = 0$$



For α =0 -> ice front.

$$P = \frac{\rho_{ice} g H^2}{2} - \frac{\rho_{water} g b^2}{2}$$

For α =1 -> rift fully filled with ice.

$$P = 0$$

For a rift filled with water, imbalance between ice and water pressure tends to close rift.

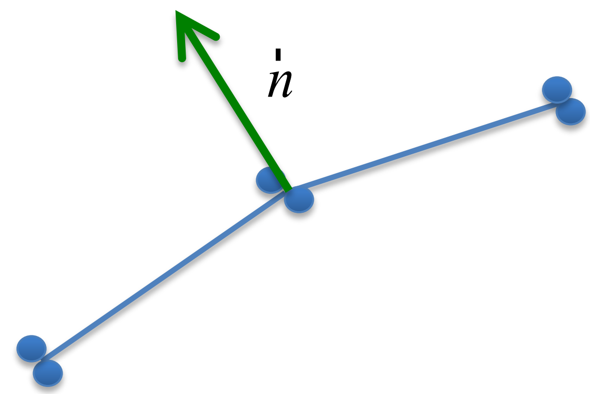
For a rift filled with ice, pressure is fully compensated, and opening is favored, provided longitudinal stress is tensile.

Boundary conditions for closing fault:

Penalized normal penetration:

$$\sigma_n = -K_{\max} 10^{\lambda} \Delta V_n$$

$$Kn = K_{\max} 10^{\lambda} \begin{bmatrix} n_x^2 & n_x n_y & -n_x^2 & -n_x n_y \\ n_x n_y & n_y^2 & -n_x n_y & -n_y^2 \\ -n_x^2 & -n_x n_y & n_x^2 & n_x n_y \\ -n_x n_y & -n_y^2 & n_x n_y & n_y^2 \end{bmatrix}$$

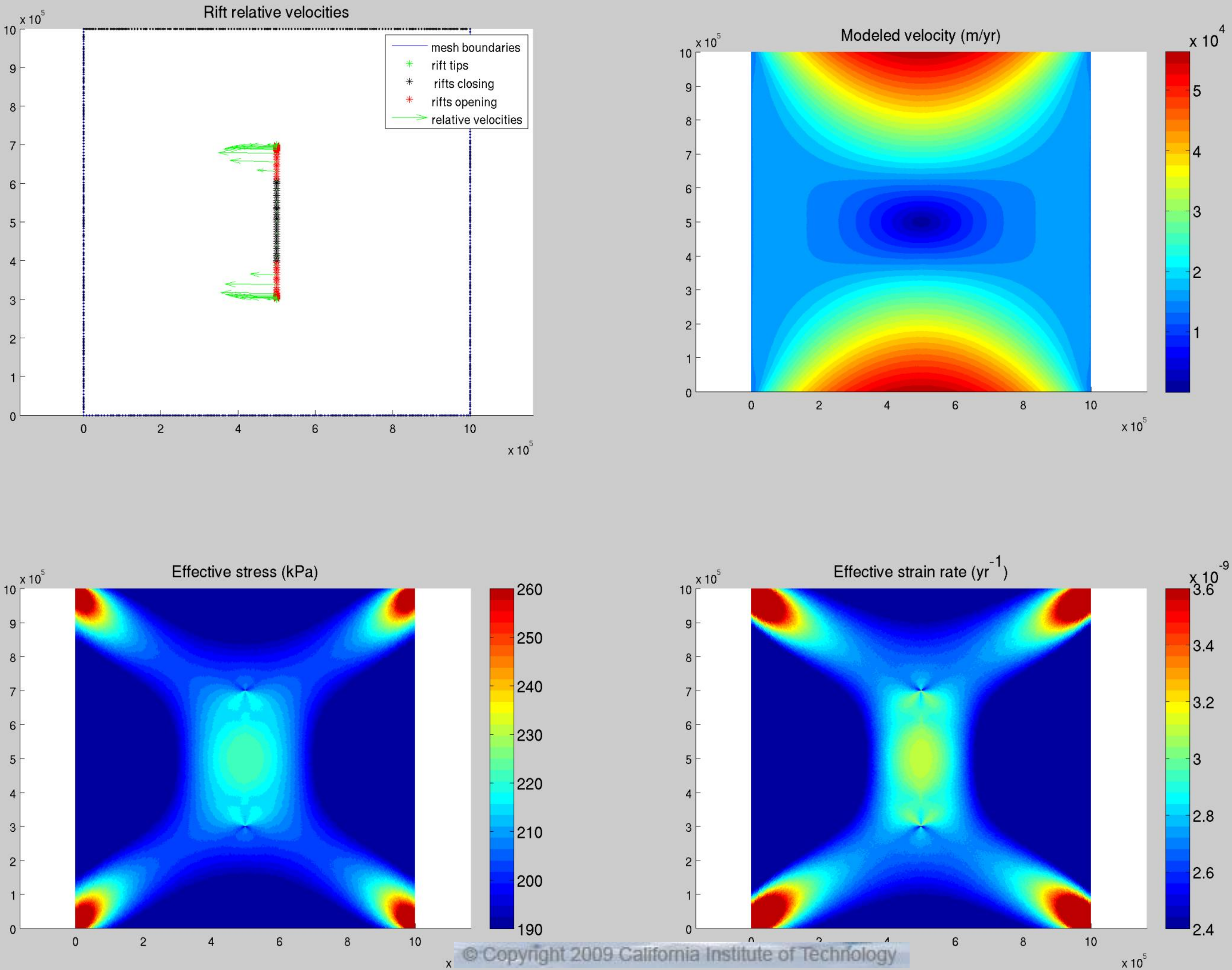


Tangential linear friction:

$$\sigma_t = f * H * l * \Delta V_t$$

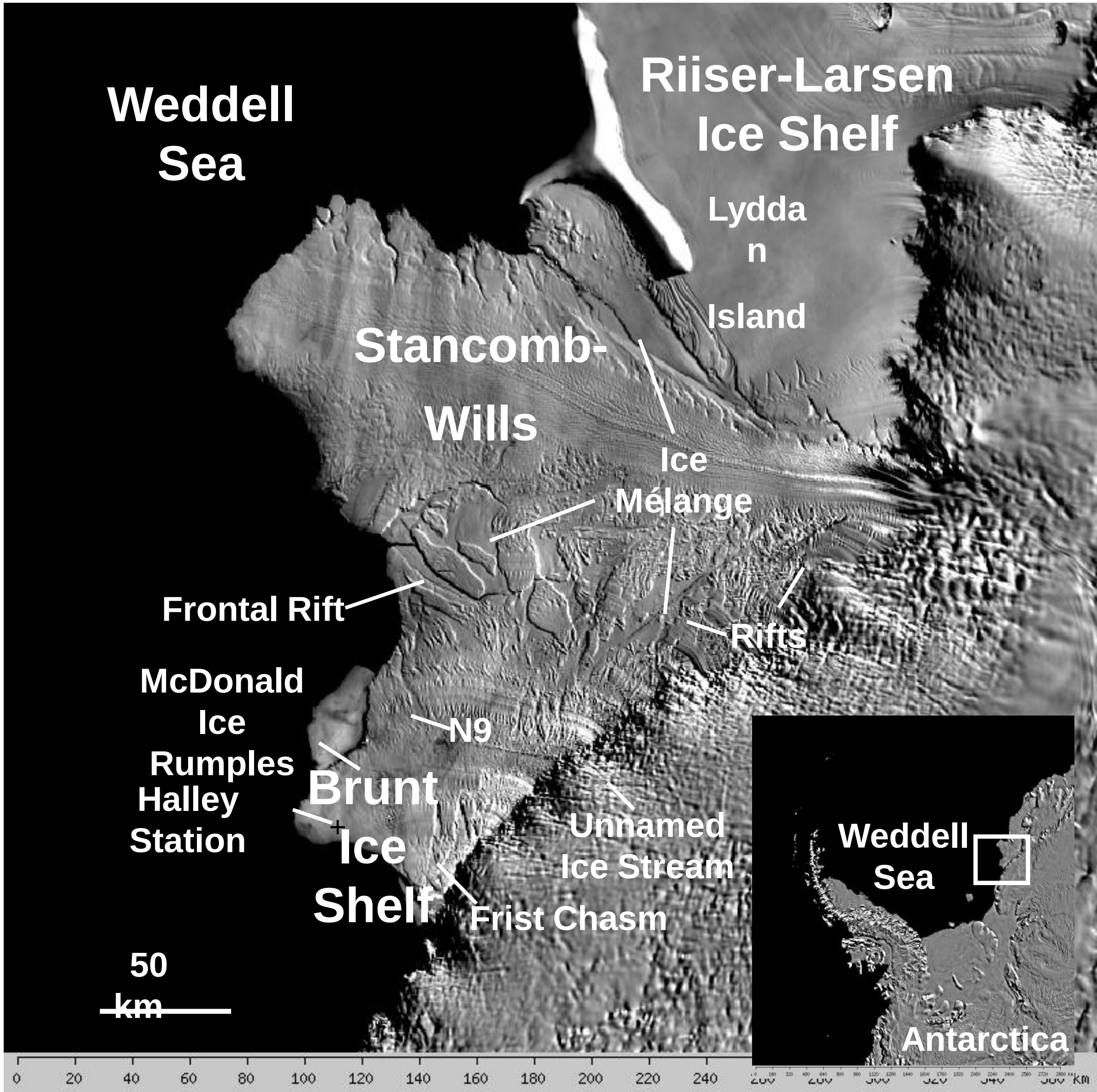
$$Kt = H.l.f \begin{bmatrix} n_y^2 & -n_x n_y & -n_y^2 & n_x n_y \\ -n_x n_y & n_x^2 & n_x n_y & -n_x^2 \\ -n_y^2 & n_x n_y & n_y^2 & -n_x n_y \\ n_x n_y & -n_x^2 & -n_x n_y & n_x^2 \end{bmatrix}$$

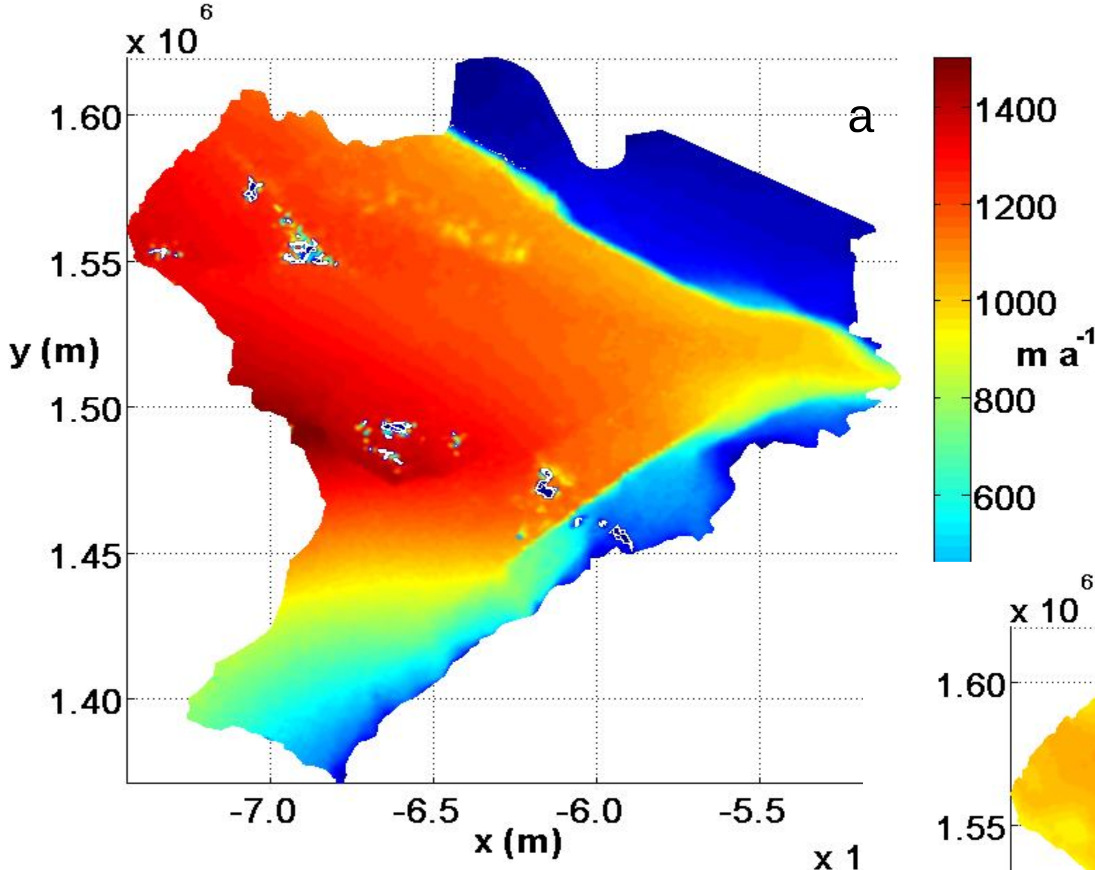
Kmax: maximum stiffness matrix
λ: penalty offset.
H: ice thickness
l: segment length
f: friction coefficient.


Rift relative velocities
x 10^5
mesh boundaries
rift tips
rifts closing
rifts opening
relative velocities
Modeled velocity (m/yr)
x 10^4
Effective stress (kPa)
260
250
240
230
220
210
200
190
Effective strain rate (yr^-1)
x 10^-9
3.6
3.4
3.2
3
2.8
2.6
2.4

3 Brunt Ice Shelf.

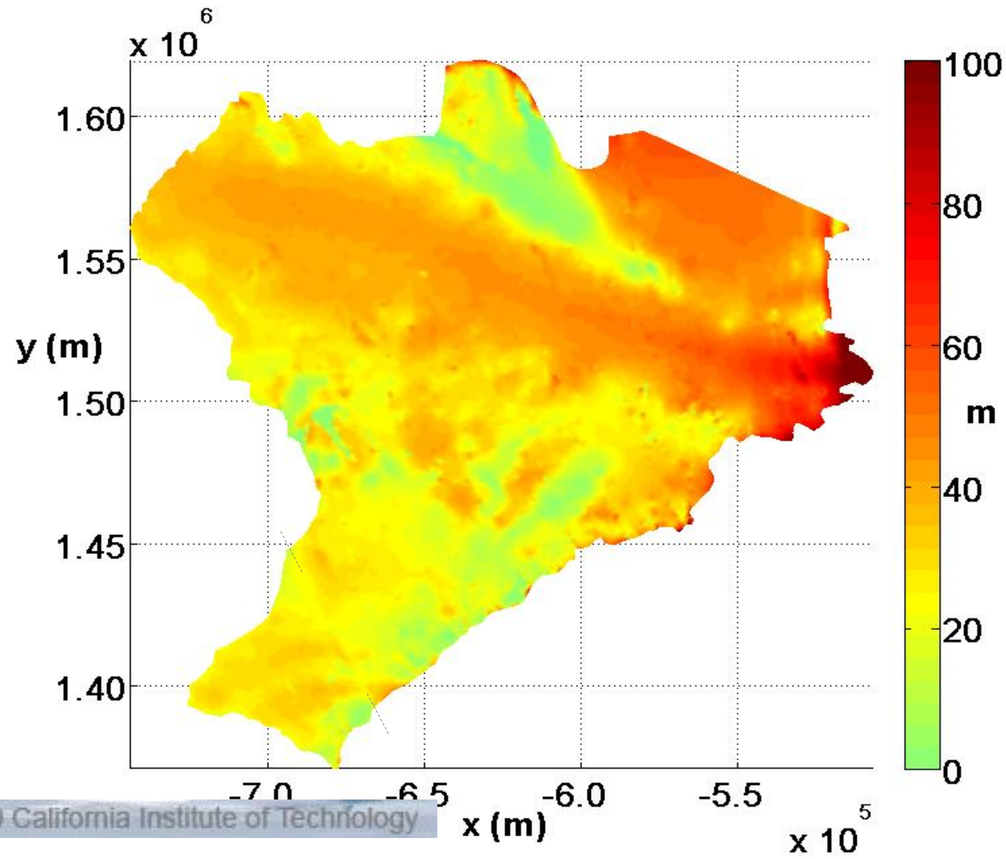
•Radarsat-1 speckle-tracking surface velocity acquired in 2000.
•Grounding line inferred from ERS-1/2 data (from 1996 for fast flow areas) and RADARSAT-1 (from 2000 for slower moving areas) using double difference Interferometry.
•Ice shelf elevations from the GLAS/ICE Sat laser altimeter digital elevation model of Antarctica [DiMarzio et al., 2007].
•Firn estimates from van den Broeke [2006, 2008].

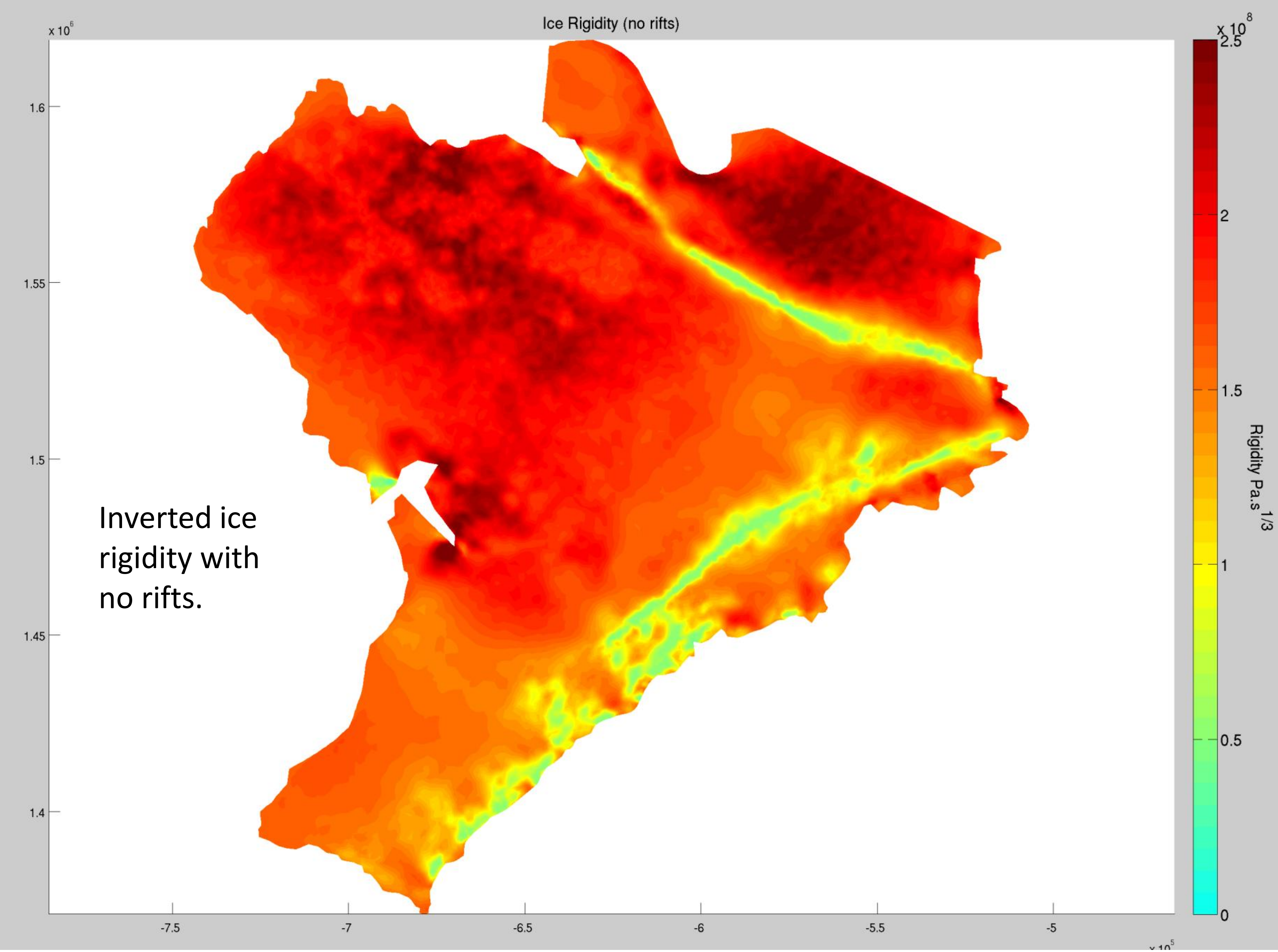




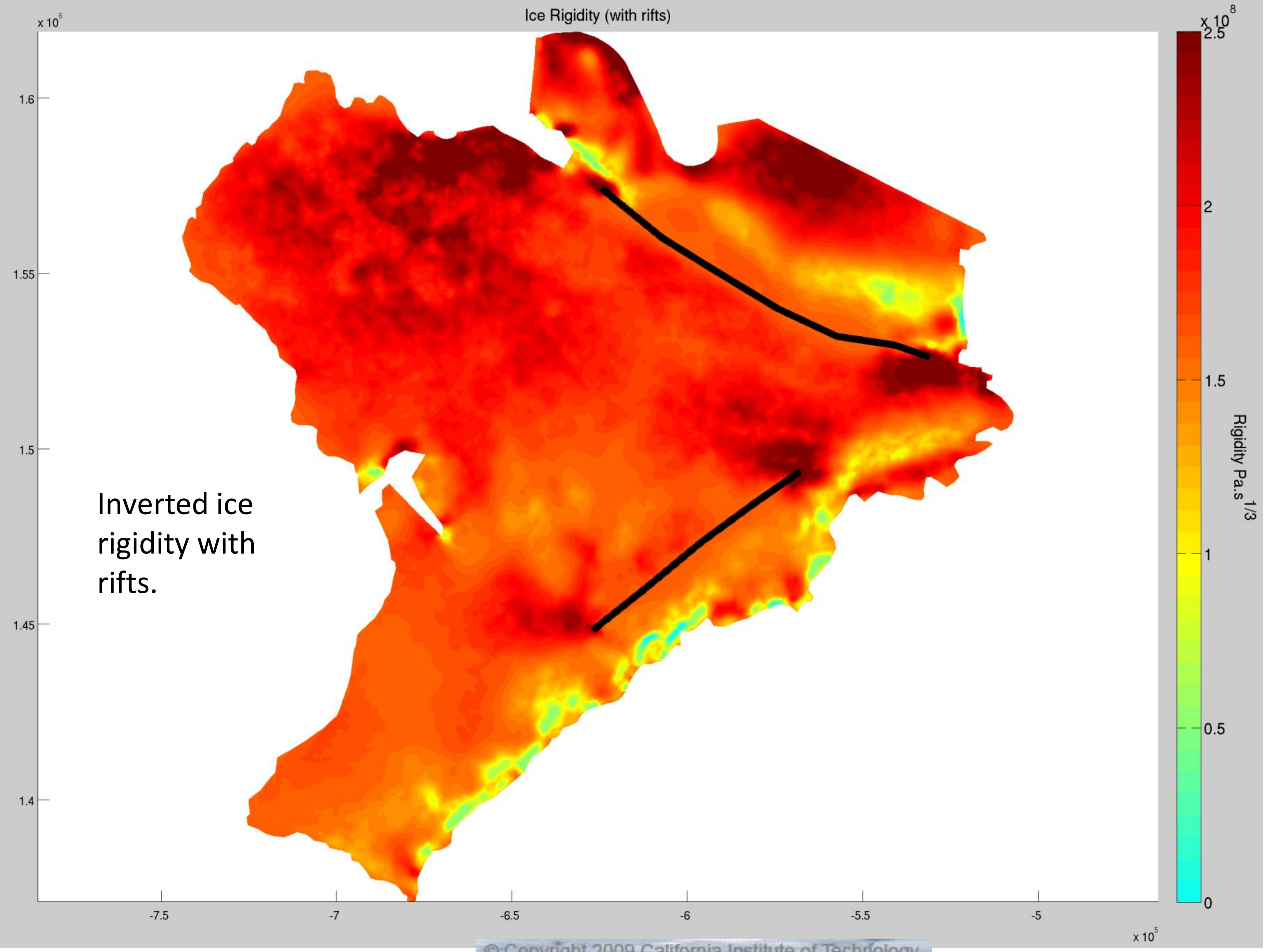
Surface Velocity (2000)

Surface DEM.

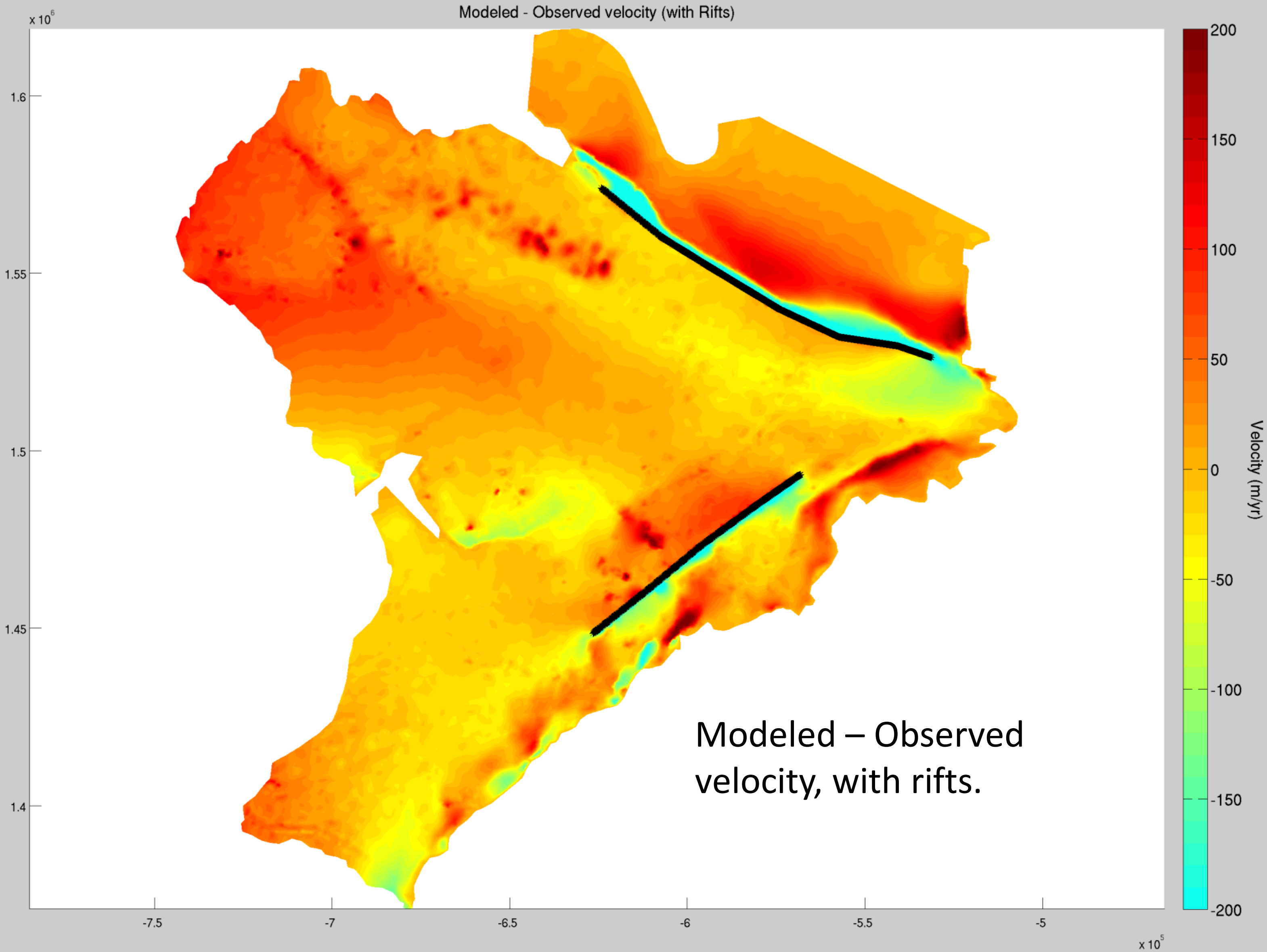




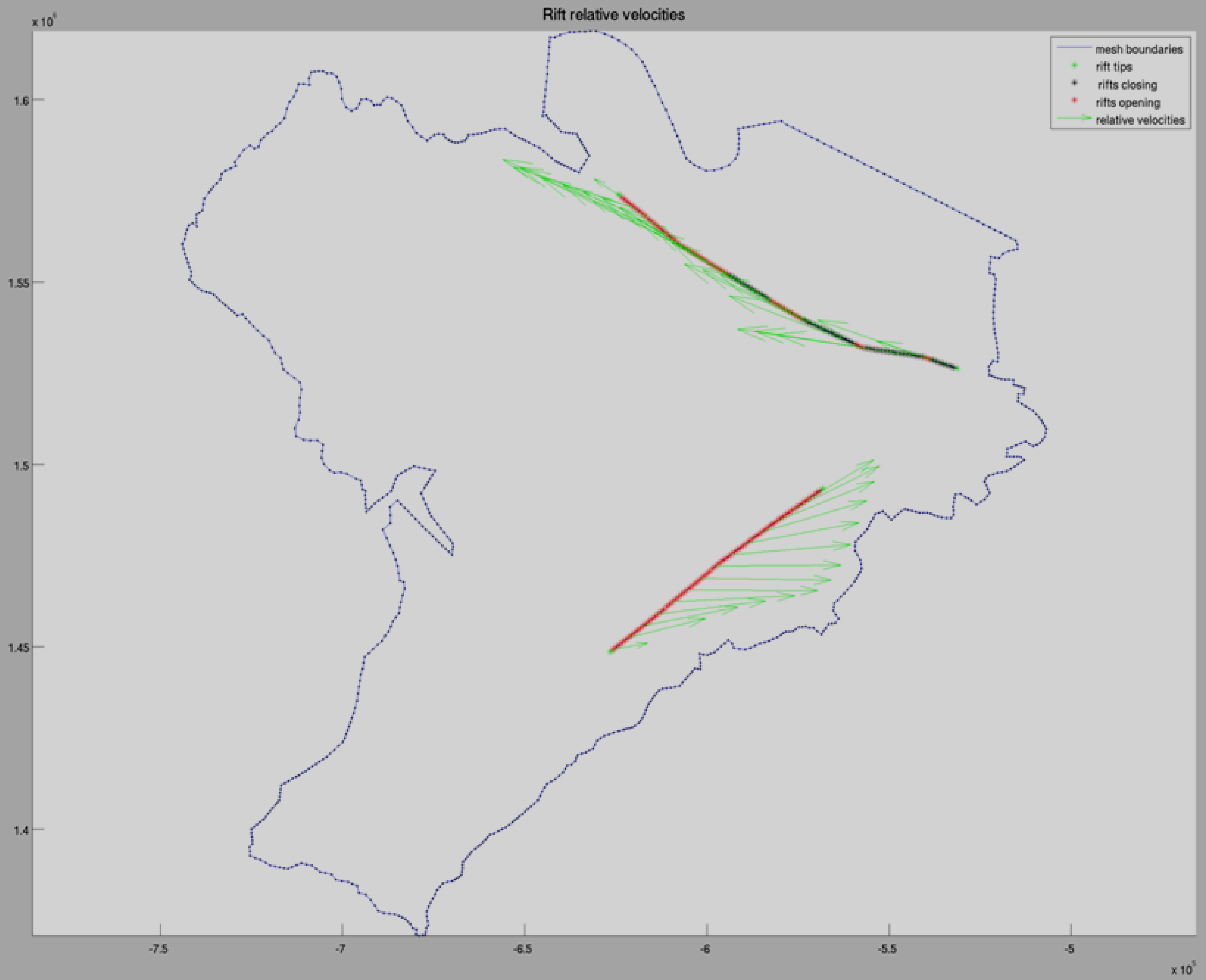
Inverted ice rigidity with no rifts.



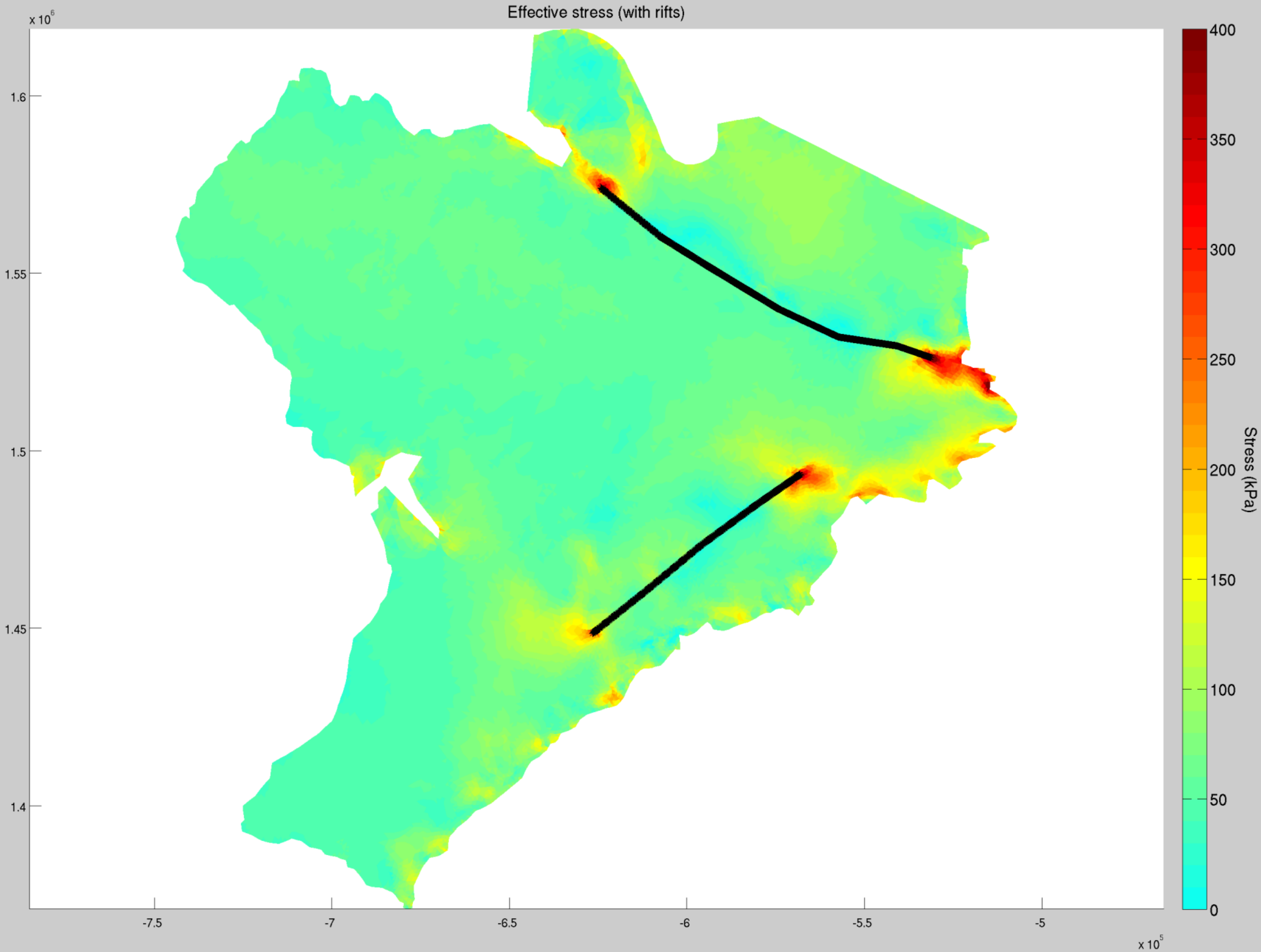
Inverted ice rigidity with rifts.



Modeled – Observed velocity, with rifts.



Rift relative velocities
x 10^6
1.6
1.55
1.5
1.45
1.4
-7.5
-7
-6.5
-6
-5.5
-5
x 10^5
mesh boundaries
rift tips
rifts closing
rifts opening
relative velocities

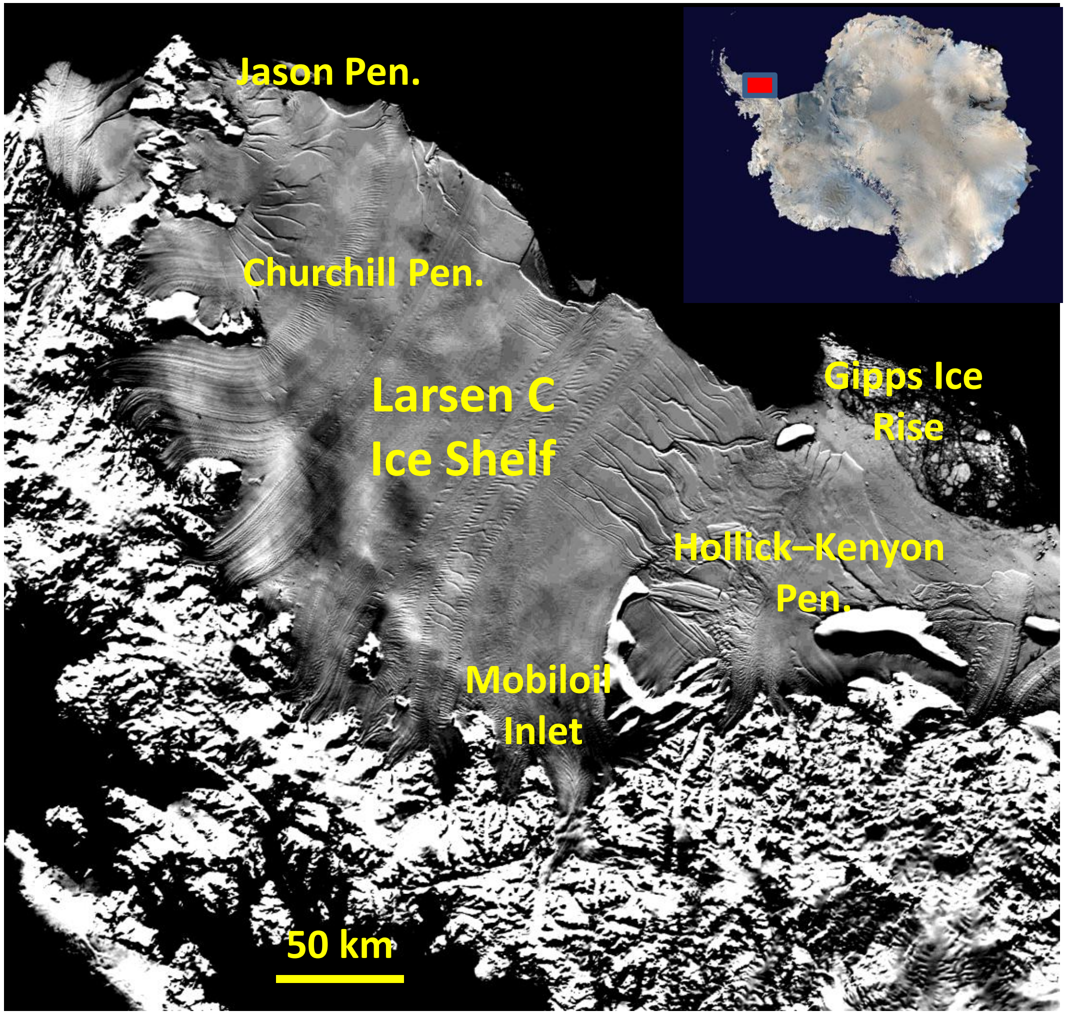

Effective stress (with rifts)
x 10^6
1.6
1.55
1.5
1.45
1.4
-7.5
-7
-6.5
-6
-5.5
-5
x 10^5
Stress (kPa)
400
350
300
250
200
150
100
50
0

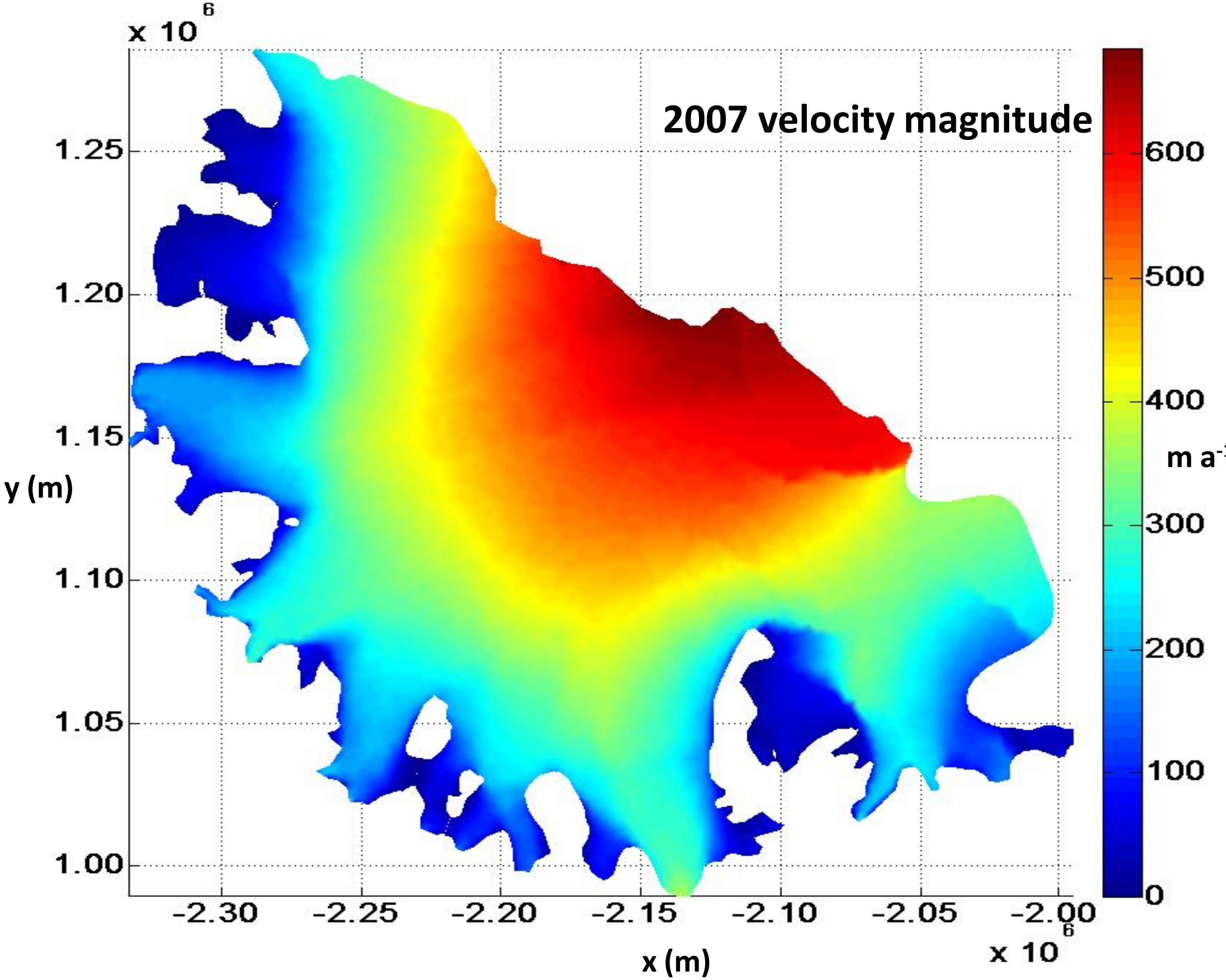
4 Larsen C Ice Shelf.

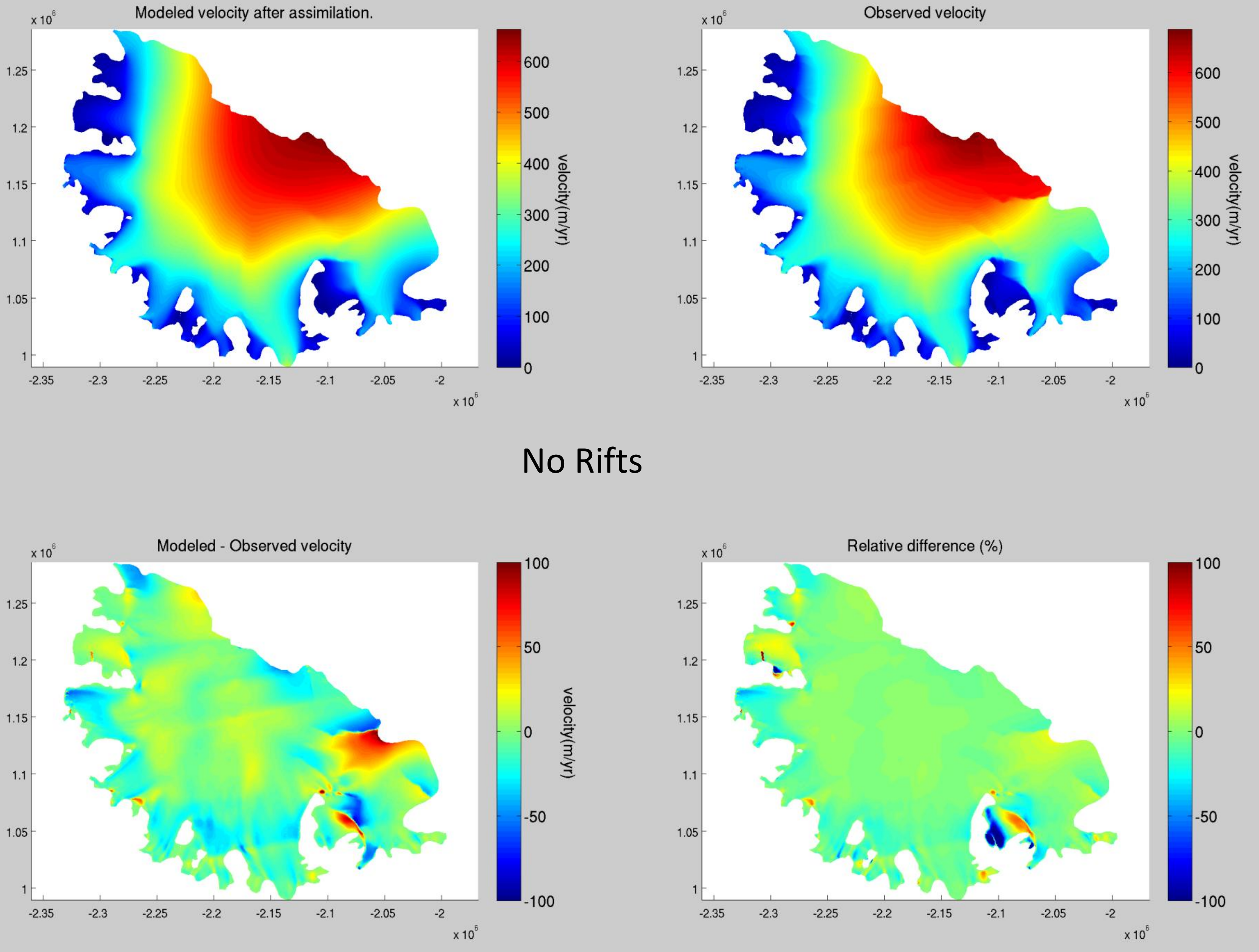
- Ice thickness by *Griggs and Bamber* (2009) obtained from ERS-1 RA data.
  Corrections made for tidal movement and firn.
  Resolution = 1 km.
  Mean random error = 47.3 m.

- Grounding line by double difference interferometry on ERS-1/2 data (march 1996).
  Error: ± 100 m.

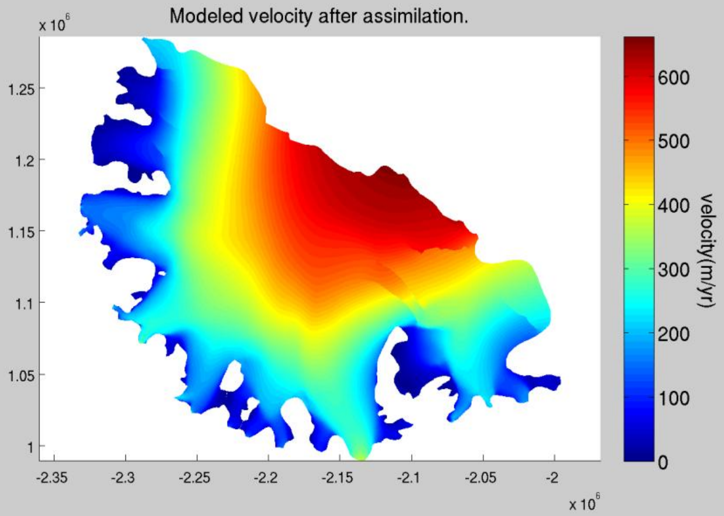
- Year 2007 (Oct.-Dec.) ice velocity by speckle tracking on ALOS PALSAR data. Error: ± 5 m a^{-1}.

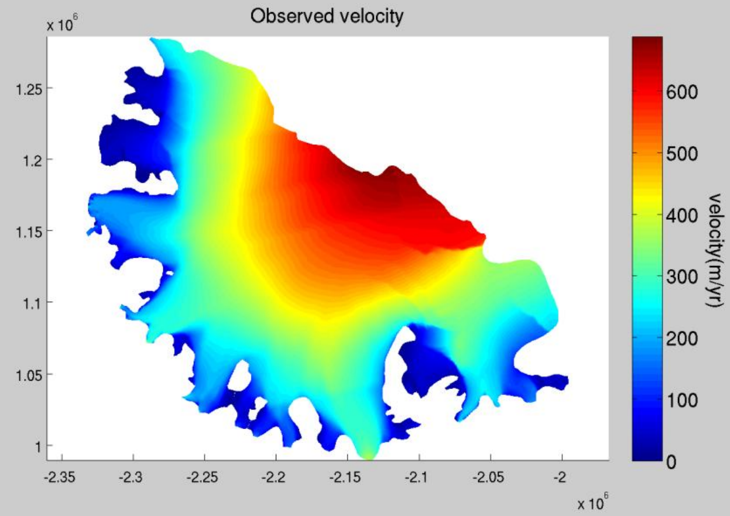



2007 velocity magnitude
x 10^6
1.25
1.20
1.15
1.10
1.05
1.00
y (m)
-2.30
-2.25
-2.20
-2.15
-2.10
-2.05
-2.00
x 10^6
x (m)
600
500
400
300
200
100
0
m a^-1

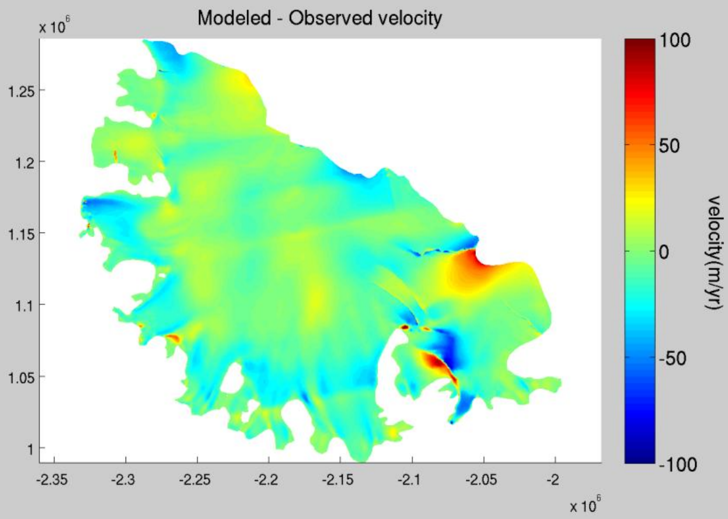

Modeled velocity after assimilation.
Observed velocity
Modeled - Observed velocity
Relative difference (%)
velocity(m/yr)
x 10^6

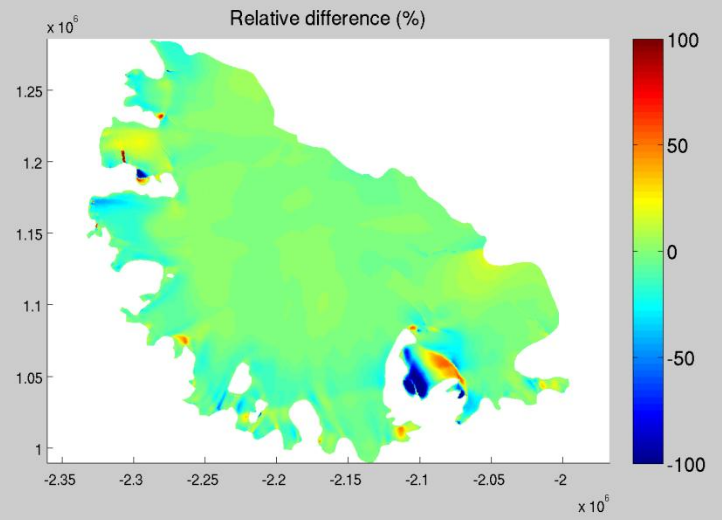
No Rifts


Modeled velocity after assimilation.
x 10^6
1.25
1.2
1.15
1.1
1.05
1
-2.35
-2.3
-2.25
-2.2
-2.15
-2.1
-2.05
-2
x 10^6
600
500
400
300
200
100
0
velocity(m/yr)

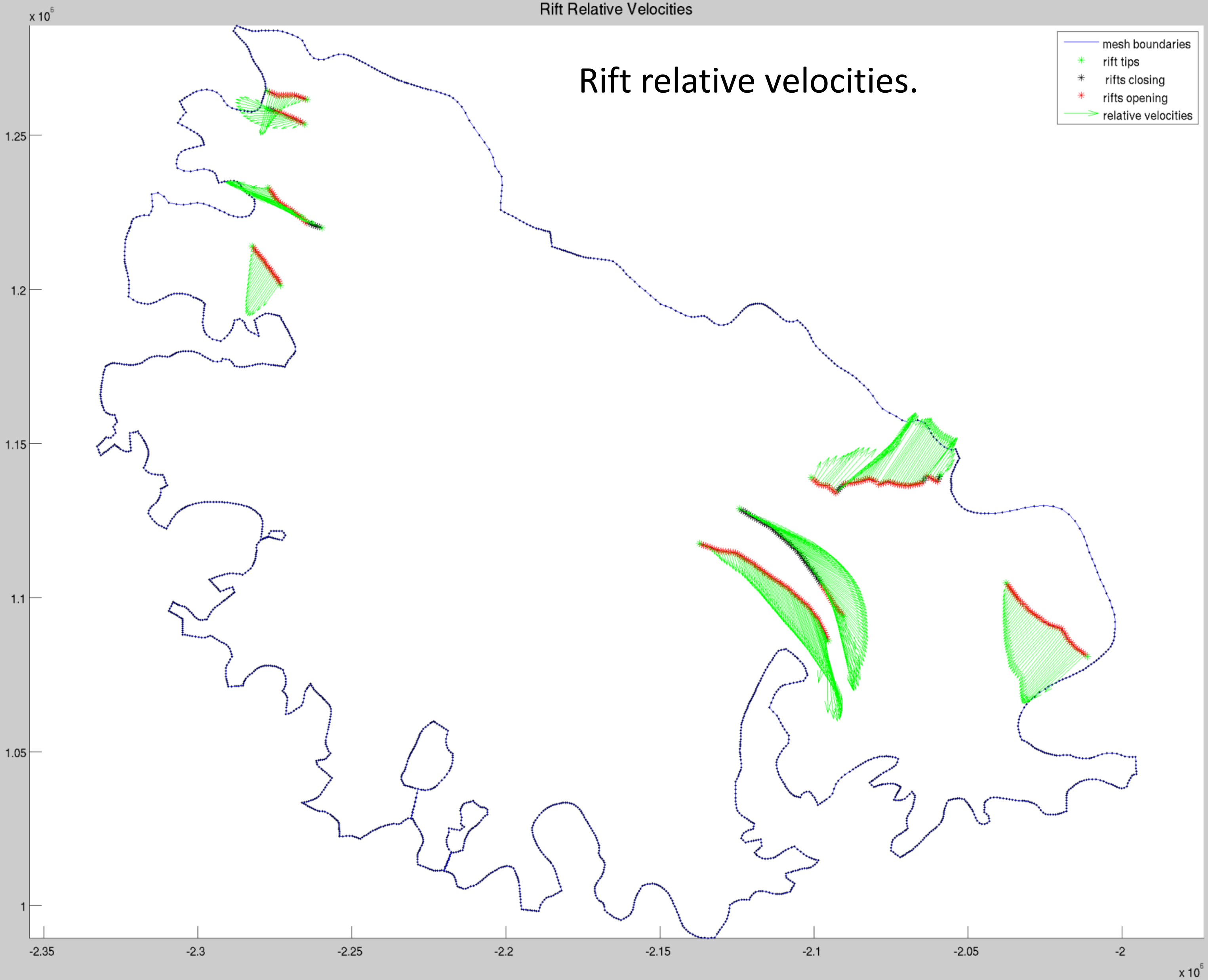

Observed velocity
x 10^6
1.25
1.2
1.15
1.1
1.05
1
-2.35
-2.3
-2.25
-2.2
-2.15
-2.1
-2.05
-2
x 10^6
600
500
400
300
200
100
0
velocity(m/yr)

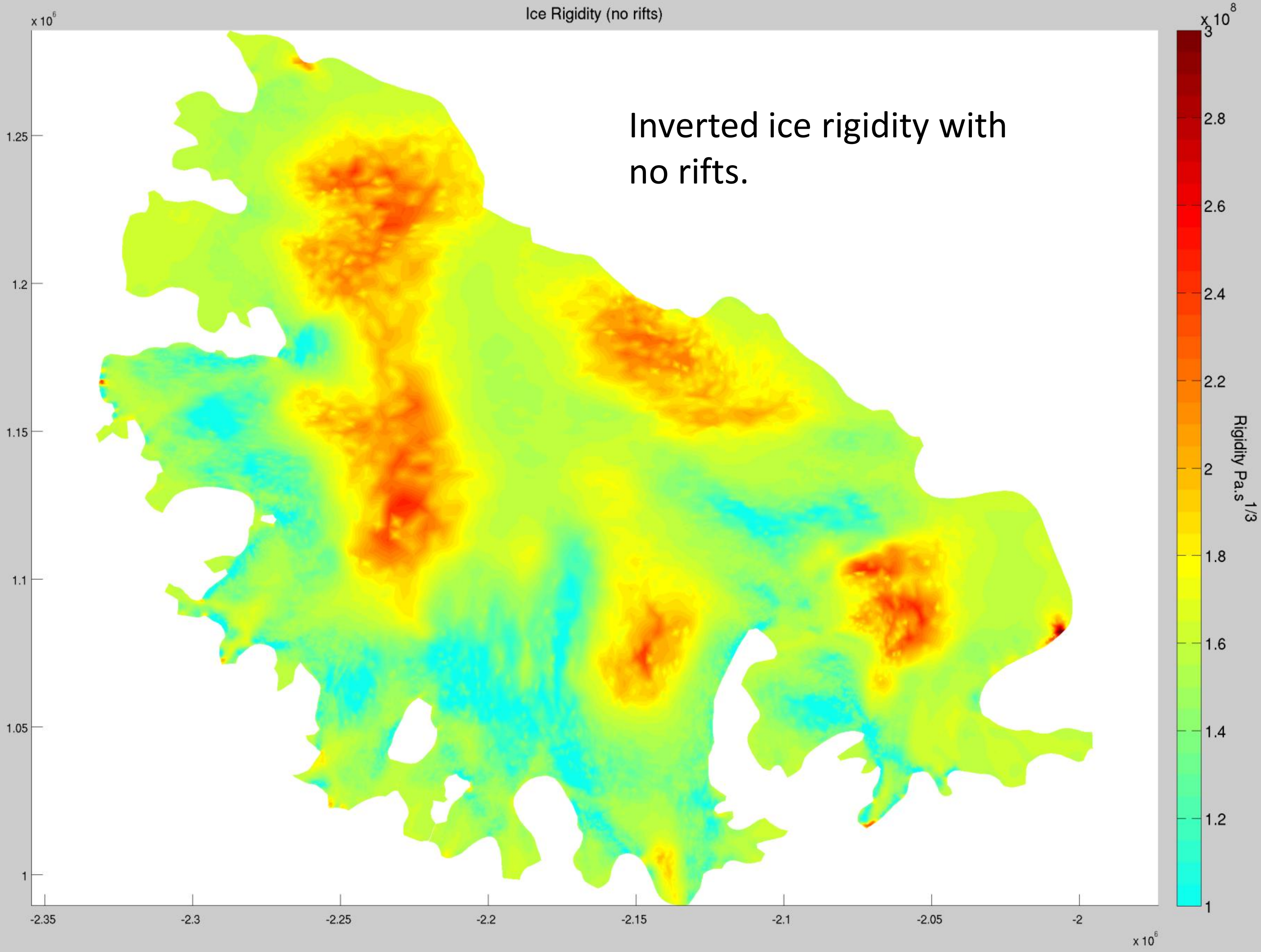
With Rifts


Modeled - Observed velocity
x 10^6
1.25
1.2
1.15
1.1
1.05
1
-2.35
-2.3
-2.25
-2.2
-2.15
-2.1
-2.05
-2
x 10^6
100
50
0
-50
-100
velocity(m/yr)

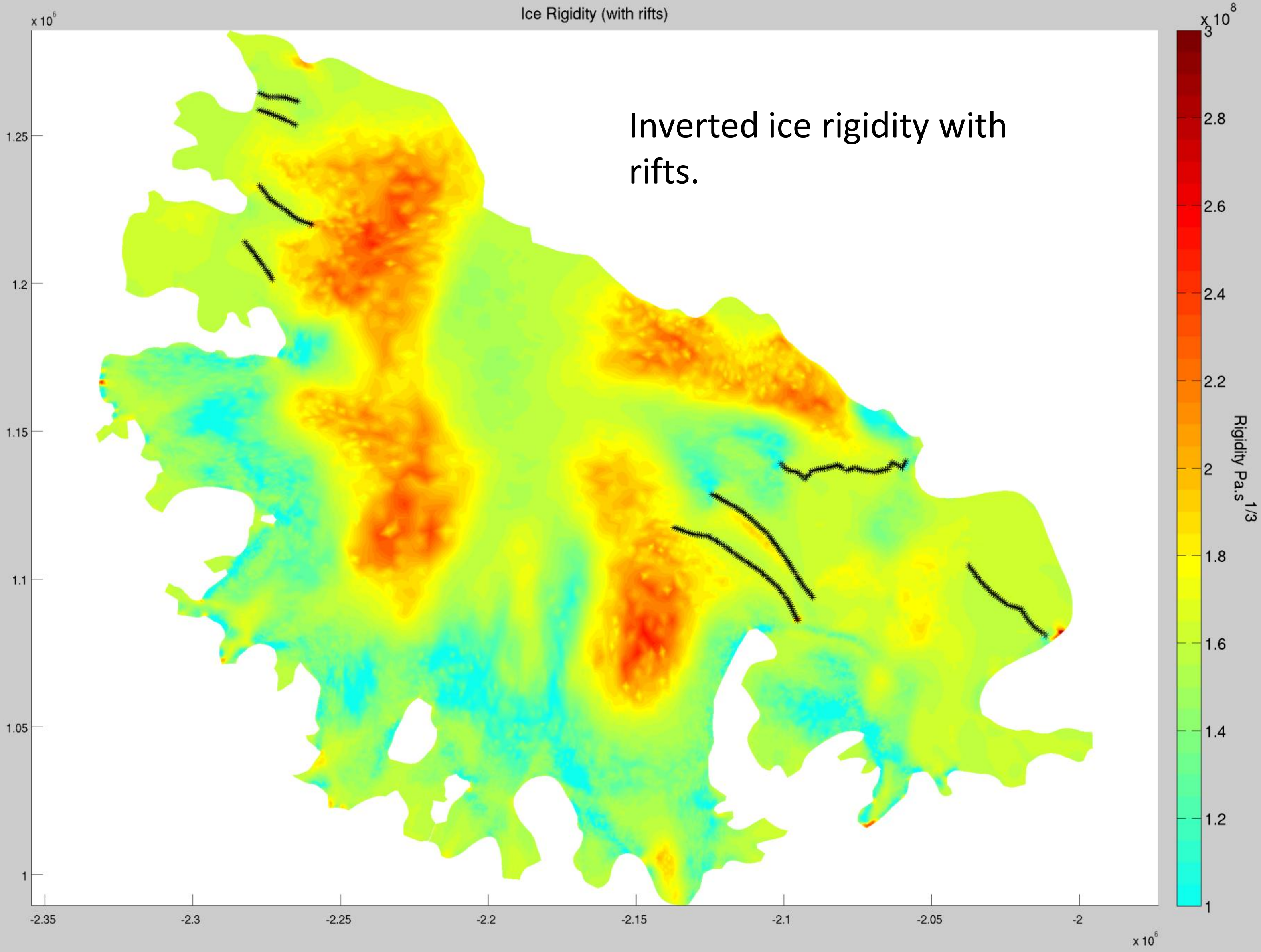

Relative difference (%)
x 10^6
1.25
1.2
1.15
1.1
1.05
1
-2.35
-2.3
-2.25
-2.2
-2.15
-2.1
-2.05
-2
x 10^6
100
50
0
-50
-100

Rift relative velocities.





Inverted ice rigidity with no rifts.



Ice Rigidity (with rifts)
Inverted ice rigidity with rifts.
x 10^6
1.25
1.2
1.15
1.1
1.05
1
-2.35
-2.3
-2.25
-2.2
-2.15
-2.1
-2.05
-2
x 10^6
x 10^8
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
Rigidity Pa.s^1/3

5 Conclusions.

- Rifts and faults can be modeled using contact mechanics principles. Stabilization of "wiggling" effect possible using melange fraction.
- Ice flow models can accurately account for delta-velocity across rifts, and tangential friction between flanks for faults.
- Rifting/Faulting processes can be used in ice rheology inversions.
- New model allows for better ice rheology inversions, where rigidity of ice does not have to accommodate for breakdown in continuum mechanics.

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